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# Jetski-Based Nearshore Bathymetric and Current Survey System

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## ABSTRACT

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Nearshore coastal research programs need a methodology for determining the bathymetry and currents in and near the surf, a region notably difficult to survey in the presence of even moderate waves. A reasonably portable system has been designed and constructed that provides survey data on these variables in the nearshore along remote coastlines using either a jetski or amphibious vehicle. The on-board measurements include 3-D positions obtained using real-time kinematic, Global Positioning System, boat orientation measurements obtained from an inertial measurements unit, and water depth estimates obtained from a precision echo sounder. The result is a low noise measurement of the bottom topography directly in the WGS84 geodetic datum, with no requirement for tidal adjustment. The system also includes an acoustic doppler current profiler to provide vertical profiles of the horizontal current. The depth values are accurate to better than 10 cm (2 sigma), tide levels to better than 5 cm (1 sigma), and current values to better than 5 cm/s (1 sigma) in careful comparisons with standard, independent measurements.

**ADDITIONAL INDEX WORDS:** *Coastal, bathymetry, hydrographic surveying, echo sounder, GPS, ADCP*

## INTRODUCTION

A basic need of research programs working on nearshore processes is an instrumented boat that can be launched and recovered over the beach, and which is usable in a range of moderate to rough sea states in a variety of remote locations. The boat must be able to accurately measure bathymetry, currents, and wave heights while in the presence of these waves. A potential guide for the accuracy of bathymetry is the International Hydrographic Organization's standard requiring a 90% probability that the errors in depth measurements do not exceed 30 cm out to 30 m depth and do not exceed 1% of the measurements at depths greater than 30m (IHO, 1987). A useful guide for currents, which have magnitude of order 0.5–1 m/s in rips and in the along shore drift, is within 10% of the actual value, or about 10 cm/sec, on spatial scales of tens of meters and more. The surface wave spectrum also is of interest, particularly near and in the surf, and a reasonable accuracy requirement is 10% of the wave height if greater than 0.3 m, with about the same accuracy level for the frequency of the dominant peak of the swell. These needs have not been addressed adequately until the recent application of modern technology, both for the platform and the instrumentation.

In preparation for an extensive measurement program in and near the surf on energetic beaches, researchers at Oregon State University (OSU) began to experiment with a jetski (BEACH *et al.*, 1996, CÔTÉ *et al.*, 2000). These small, lightweight boats have a high power-to-weight ratio so that they are very maneuverable and can accelerate out of the danger of large breakers. In addition, they are rugged and watertight so that they do not sink and can be easily righted if inadvertently upset. At that time (circa 1995), the OSU group was using a differential GPS (DGPS) receiver on their boat to measure the horizontal location (to about 2 m accuracy) and a fathometer to measure the distance from the transducer to the bottom. The vertical accuracy of typical commercial DGPS receivers, however, is only 3–4 m, so the actual depth had to be estimated by averaging the fathometer data to reduce the contamination due to wave motion, and adjusting the residual mean signal level to the local tide level. This approach was novel, but the rather inaccurate differential correction was inadequate for achieving our accuracy goal. Also, the need for adjustment to the local (estimated) tide level when operating in and near the surf was awkward, and it was clear that these limitations could be removed by using newer technology, namely the recently introduced (at that time) real-time kinematic, GPS (RTK GPS).

The Areté Associates Washington Office has developed an instrumented jetski called SCAMP, for Surf and Coastal Area Measurement Platform, which has successfully extended RTK GPS survey accuracy into the nearshore, including the surf-zone. During the period between January 1996 and November 1999, SCAMP was used in six field tests including a series of tests performed at the US Army Corps of Engineers Field Research Facility (FRF) at Duck, NC and a separate test conducted on the Oregon coast near Newport. This capability to operate a highly mobile survey boat from the beach to provide accurate data in a range of weather condi-

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tions and in a variety of remote locations is truly unique. The low weight and rapid acceleration of this type of boat are critical attributes for launching and recovering it from the beach, and safely maneuvering between the breakers in the surf. Additionally, this instrumentation is portable. The RTK GPS has been mounted on a 4WD all-terrain vehicle (ATV) which has allowed us to include the coastline topography of the beach from dunes to waterline. The ATV is deployed during low tide to get the beach height as far into the water as possible and the jetski is deployed during high tide to get crossover measurements with the ATV. In addition, the system has been installed on the FRF LARC-5 (Lighter Amphibious Re-supply Cargo) a Navy Harbor Security Boat (HSB), and a Canadian Forces launch.

The RTK GPS approach does require the extra effort of installing a base station surveyed to a locally established geodetic monument instead of relying on a commercial or Government provided differential GPS signal source. However, this added preparation effort is more than offset by the operational gains. The RTK GPS approach offers a substantially improved position performance, and eliminates the need for local tide measurements and the requirement to apply spatial averaging to compensate for variations due to the waves. As a result, the RTK GPS approach has an improved ability to resolve smaller scale physical features on the bottom such as a bar-trough structure. In addition, the highly accurate velocities that are available from a RTK GPS system have enabled us to include ocean surface current measurements in our nearshore surveys.

The system was designed, constructed and tested, and has been used to provide a number of nearshore surveys on rather remote beaches (*i.e.*, remote from the nearest safe harbor entrance) and in a variety of weather conditions. The next two sections describe the overall concept, details of the design, expected performance, and operating procedures. This is followed by a description of the analysis of data sets that were collected to estimate the operational accuracy of the depths and currents, and, finally, by summary comments and conclusions.

## SYSTEM DESCRIPTION

The schematic in Figure 1 illustrates the principle of using a RTK GPS receiver for conducting bathymetric surveys and current measurements. The boat has both an L1/L2 GPS antenna and a radio receiver (with associated antenna) for receiving the corrections from the nearby GPS base station. The base station is set up on, or related to, a local geodetic monument. The radio link to provide real-time RTK GPS not only avoids the need for post-processing to accomplish GPS error corrections, but also enables real time navigation to a planned survey grid. A waterproof box on the stern holds the electronics for the GPS receiver, the radios, and the current meter, and a laptop PC for recording the data. Also in the electronics box are serial data interface modules to the radio and laptop PC that enable the merging and changing of baud rate for each of the sensor inputs. An inertial measurement unit (IMU) is mounted under the driver/operator seat and the antenna for receiving the L1/L2 GPS signals is near the stern. There are actually two telemetry radios with associated antennas. One is for receiving the GPS correction signal and the other is for transmitting the bathymetric data from the boat to a duplicate recording system on the beach. Both recording systems run standard hydrographic software for recording and displaying the data. The one on the boat records only, while the one on the beach also has a display so that an operator can monitor the progress of the survey and provide steering instructions to direct the driver along the survey lines. The driver has a voice activated radio that is used for communications with the beach. Thus, he is not distracted by having to key a radio nor by having to observe and interpret a display, and can concentrate on maneuvering safely among the waves in shallow water. The fathometer transducer is glassed into the hull and the current meter (either a single point electro-magnetic sensor or a profiling ADCP) is on a driver-deployable mount on the stern. A digital compass provides the boat heading so that the EM current meter data can be translated into the geodetic reference frame.

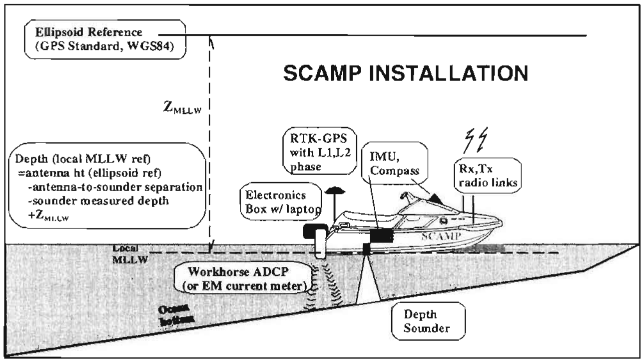

Figure 1. The SCAMP installation is comprised of a jetski equipped with RTK GPS, an echo sounder, a current sensor, onboard electronics and radio links to a GPS base station and a survey control monitoring station on shore. The RTK GPS vertical measurement yields cm-level accuracy to the WGS84 ellipsoid reference. That reference is easily transferred to a local vertical datum eliminating the effects of local water level variations.

The RTK GPS receiver measures the 3-D position of the phase center of the antenna in the WGS84 geodetic datum, and makes the corrections on the fly. The echo sounder measures the interval between the initiation of a transmitted pulse and the capture of the received reflection from the bottom, which is proportional to the transducer line-of-sight distance to the bottom. The time interval is related to the vertical distance between the transducer and the bottom using the local sound velocity, the attitude of the echo sounder as measured by the IMU, and the known echo sounder beam characteristics. These position and distance measurements are combined with the distance between the GPS antenna and the transducer and translated directly to the local tidal datum by the known relationship between the WGS84 coordinate frame and the datum.

Figure 2 is a photograph of the system as observed in the surf. The GPS receiver antenna is seen on the after port side, the base station receiver antenna on the after starboard side,

Figure 2. A photo of SCAMP in action.

the transmitter antenna forward of the driver, and the electronic box on the stern. Not seen is a voice radio with a miniature antenna inside the driver's helmet and its voice-activated transducer in an ear-piece.

The data are recorded on a laptop PC in the electronics box, and the positions and echo sounder data are combined via serial interface modules and transmitted to the monitoring station as noted previously. Both laptops run a version of Coastal Oceanographics' HYPACK survey and data collection software. The onboard laptop records all channels of data and the one on the shore displays the positions and the echo sounder data, serving as a real time data quality check and as real time input for directing the survey lines.

After the survey, the data are screened for errors and processed for the final bathymetry results. The screening includes the removal of non-kinematic GPS posits, spurious sounder returns and those GPS-sounder pairs that fall outside our synchronization requirements. The GPS receiver identifies non-kinematic positions in its transmitted data packet and this information is used to flag those points for removal from processing. The echo sounder also attaches an error flag in the transmitted data packet of known bad soundings, however, there are generally additional spurious sounder returns that do not get flagged. To remove these obviously erroneous returns, a statistical check is performed on the sounder time series. Using a sliding window technique, echo sounder returns that are larger than three standard deviations from the window's mean are flagged for removal. Finally, the data are aligned in time using cross-correlation techniques and only those matched pairs of RTK GPS heights and sounder estimates that have synchronization error estimates less than 50 msec are retained. The remaining data are put in scientific units, and the corrections and sums are computed.

This bathymetric system also has been installed on an amphibious truck, the FRF LARC-5 work boat, which is similar in design and operation to the amphibious DUKW included in the beach profile study of the Oregon and Washington coasts by KOMAR (1978). In order to eliminate the boat motion difficulties described by KOMAR (1978), the FRF LARC-5 had previously used a towed sled and optical tracking system to determine the location of the sled and the depth of the runners. More recently, the LARC-5 was equipped with this system and was successfully tested against the FRF bathymetric standard, the Coastal Research Amphibious Buggy (CRAB) as reported in DUGAN *et al.* (1999), and it has subsequently been used to conduct surveys in Oregon Inlet, NC. The LARC-5 has the advantage that it can get up and over offshore shoals, whereas the jetski cannot. On the other hand, the jetski can operate more safely in the surf and it can work successfully in rougher waves outside the surf, so it can be used in a wider range of conditions. It also can be used in conjunction with an ATV with the same RTK GPS receiver onboard to conduct joint nearshore-beach surveys, as noted previously. In addition, the jetski can be used to measure water currents, whereas the LARC-5 has such a distorted flow around its hull that it cannot.

There are two options for measuring water currents on the jetski. The first is to use a rugged Marsh-McBirney electromagnetic (EM) current meter, which outputs the 2-D vector flow past its 1.5-inch sensor head. The sensor is installed on a staff lowered over the stern quarter, resulting in a sensor depth of about 45-cm (30-cm below the keel depth). The analog output range is 4 m/s, and this is transformed to RS-232 using a custom-made analog-to-serial board yielding a resolution equivalent to approximately 1 cm/s. The two-channel current data are recorded along with the RTK GPS-derived boat velocity and the heading measured by a digital compass. A vector subtraction of the current meter velocity from the RTK GPS-derived boat velocity yields a vector estimate of the water velocity over the bottom.

The EM surface current meter installation was augmented with an RD Instruments Workhorse model ADCP to extend our ability to measure currents through the water column. The ADCP is a 1200 kHz unit equipped with bottom-track capability. It is secured in a customized two-position mount on the rear of the jetski. In its deployed position, the ADCP transducer face is about 0.5 m below the surface. The ADCP is pre-programmable using RD Instruments embedded software. It has a built-in compass with a menu driven calibration procedure, and a resulting compass error of 2 degrees. The programmed settings we have used provide single ping velocity profile data at a rate of 2 Hz, a depth bin size of 0.5 m, a one meter blanking distance, a maximum depth of 15 m, and bottom-track mode enabled. Data are recorded in the ADCP coordinate frame along with heading, pitch, and roll for post-test data processing. During surveys the speed is limited to 2.5–3 m/s, and the RTK GPS locations are recorded at a rate of 5 Hz. After collection, the current profile data are transformed from instrument to earth coordinates, then the bottom-track velocities are subtracted, and the velocity profiles are averaged over 10 seconds, or approximately one dominant swell period. The expected ensemble standard deviation for the averaged data is 1.8 cm/s, assuming that the ADCP is the only noise source.

## OPERATIONAL CONSIDERATIONS

The relative accuracy of the RTK GPS measurement, when computed at a 1 Hz update rate, is about 1 cm in the horizontal and 1 to 2 cm in the vertical (LANGLEY, 1998). There is an additional 1 part-per-million degradation in relative accuracy with range from the base station. This accuracy can be maintained in absolute positioning by properly referencing the base station antenna to a locally surveyed geodetic monument. It should be noted that the vertical adjustment from WGS84 to a local datum may, or may not, be a constant value. Our experiences illustrate this point. The geoidal separation was nearly constant at Duck, NC, (0.3 cm/km), and use of a single value for the vertical adjustment over our survey area was sufficient for our requirements. However, this was not the case while operating off the Oregon coast where we found a slope to the geoidal separation that was nearly 3 cm/km, and this required an additional linear-slope adjustment in post-processing.

In higher sea-state conditions, the typical RTK GPS sampling rate of 1 Hz is not sufficient to resolve the full bandwidth of the surface wave driven boat dynamics. For those conditions, there are two available options for increasing system bandwidth to better resolve wave motions. The first is to increase the RTK GPS receiver update rate to 5 Hz, but with reduced resolution (2 to 3 cm in horizontal accuracy and 4 to 5 cm in vertical). The second option, normally reserved for very energetic wave activity, is to merge the RTK GPS signal with data from the IMU, in this case a TSS (UK) Ltd. model DMS-025. The difficulty in this last option is in maintaining synchronous measurements. Due to the high throughput of the IMU, the acquisition software can periodically and unpredictably miss data points, and the processing must be sufficiently robust to detect and properly handle this condition.

The echo sounder is a Datasonics model PSA-900 altimeter that has a conical full beam width of 8°, a recording rate of 10 Hz, a resolution of 1 cm, a 20 cm blanking distance and a 30 m full range. The 1 cm error value for echo sounder resolution is not the full accuracy of the instrument because it does not include the resulting error when the sound speed profile in the water is not known in detail. The temperature typically is known to within one degree Celsius and the salinity to within one part per thousand, and these values lead to errors in the sound speed of order 5 m/s. This uncertainty is approximately 0.3% of the sound speed for ocean water (typically 1500 m/s), so it leads to a comparable percentage error in depth estimation. In our measurements, we either use a conductivity-temperature-depth (CTD) instrument that occasionally is profiled from the boat or, for the case of measurements in the vicinity of FRF, the daily CTD profile that is collected from the seaward end of the pier. We believe the error due to this source is always less than 5 cm for water depths of 20 m and less.

As stated above, the recorded depth values are adversely affected by pitch and roll and, to a lesser degree, by heave (since those variations are, to first order, handled by the RTK GPS data). High sea conditions, therefore, require post-processing using the IMU data. The combined GPS antenna and echo sounder attitude errors have been estimated using a simple geometric model. The model has been tested through a comparison with actual measurements of the error distance obtained by rolling the boat in a controlled manner. The result is plotted in Figure 3 as a function of the roll angle of the boat. The figure is a summary of the performance of the correction algorithm employed to account for offsets in depth measurements resulting from wave-induced boat roll. The solid lines in Figure 3 are the geometrically computed offsets as a function of roll angle for zero degrees and eight degrees pitch angle. Each of the curves is a composite of the following three roll-dependent variables:

1. the change in the vertical separation distance between the onboard echo sounder and the GPS antenna,
2. the off-normal sample of the ocean bottom by the 8° conical acoustic beam, and
3. any (in our case, 5°) off-axis mounting of the echo sounder.

The model-generated curves were computed for a water depth of 8 m. The discrete-point curve represents variations in the mean depth obtained during a controlled roll test of the instrumented jetski in 8 m water depth. The close agreement between the observed and computed offsets is deemed a validation of the algorithm.

During surveys, this correction to the measured depth typically amounts to 10 cm or less, as the jetski does not roll and pitch as much as one might think for such a small vessel.

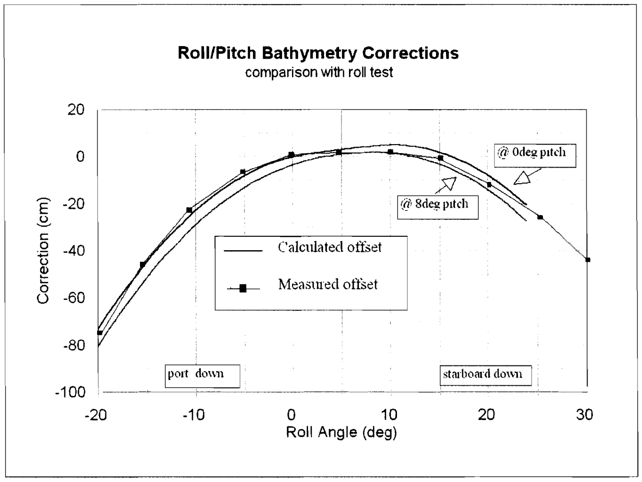

Figure 3. A comparison of computed and measured offsets as a function of roll angle.

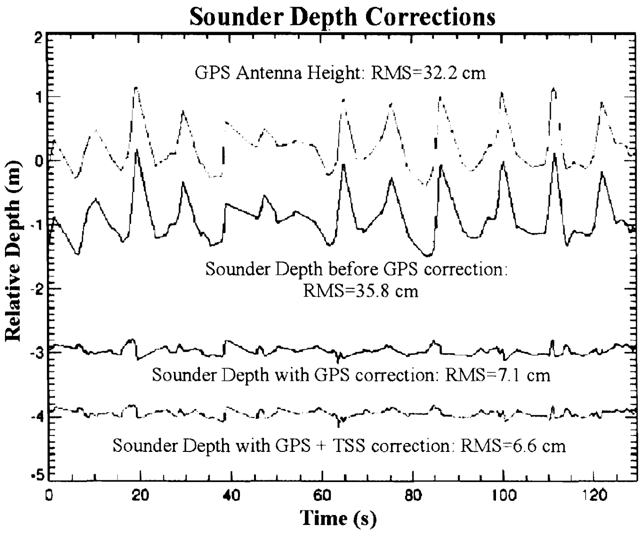

Figure 4. Time series of data collected by the SCAMP system while holding station over a flat bottom at 6 m depth and in waves having $H_{m0}$ of 1.0 to 1.3 m. Marginal improvement with TSS processing was due to inadvertent factory installation of a 4-point averaging algorithm in echo sounder output that eliminated bandwidth gain.

The ability to coherently remove boat motion and attitude eliminates several well-known problems for bathymetric surveys in shallow water. The process essentially eliminates bias and noise problems of boat squat, set down/up in the surf, and other problems commonly encountered when translating tide station measurements to the nearshore survey region. It also removes the necessity to average the data over time to reduce the wave motions that otherwise would appear in the data, and therefore enables full spatial resolution of small but important features such as the bar and trough.

## ACCURACY TESTS AND RESULTS

A test of the bathymetric data quality and the processing algorithm was made in cooperation with the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory Field Research Facility (FRF) located at Duck on the North Carolina Outer Banks. Data were collected while the boat was drifting slowly above a flat bottom (about 6-m depth) on a day when the $H_{MO}$ was 1.0 to 1.3 m. Figure 4 is a two-minute time series plot of the various channels of data. The top two channels are the GPS antenna height and the echo sounder distance that have been processed to 1 Hz, synchronous time series but not geometrically corrected for pitch and roll. Their difference is shown as the third time series which, if there were no noise and the measurements were perfectly synchronous, would be a constant value since the actual distance to the bottom did not change at the location of the boat. The geometric corrections were included for the fourth (bottom) time series, and the improvement is only fractional. This marginal improvement in noise reduction is a bit perplexing since the added bandwidth in sampling (10 Hz for the echo sounder and IMU) was expected to reduce the timing uncertainty between antenna height measurements and depth measurements and thereby reduce the standard deviation to approximately 3 cm. The quandary remained until it was learned that the echo sounder was inadvertently programmed at the factory to provide 4 ping averaging in its 10 Hz update. This averaging essentially eliminated the bandwidth advantage we thought we had. The averaging algorithm has since been removed and the effective noise reduced, but recent deployments have not afforded an opportunity to quantify the improvement for conditions of relatively high surface wave activity.

The CRAB has been the FRF bathymetric standard for nearly 20 years providing surveys to a water depth of 8 m with a standard deviation of depth error that is typically less than 3 cm (BIRKEMEIER and MASON, 1984). The CRAB measures the distance to the bottom as the fixed distance between the phase center of an RTK GPS antenna on the operations platform and the bottom of its wheels. To examine the accuracy of the SCAMP bathymetric measurements, a comparison test between the SCAMP and the FRF CRAB was conducted on May 18, 1997. The SCAMP performed a 10-line repeatability test behind the CRAB on the FRF 640-m profile line. The $H_{MO}$ on this day was 0.4 m. The CRAB and SCAMP depth profiles obtained during the test are shown in Figure 5 as a function of distance offshore. The differences obtained were 9 cm in the mean and 5 cm deviation at the 90% probability level. The mean offset is not zero as one would expect, and the source was unknown at the time of the experiment. A similar error was obtained when this same survey system was installed on the FRF LARC-5 and a comparison made with the CRAB during a separate test. A subsequent investigation found that the offset was partially due to a 5 cm error in the distance that FRF had been using between the height of the reference GPS antenna phase center and the bottom of the wheels on the CRAB (BIRKEMEIER, personal communication). The remaining 4 cm offset is depth dependent (offset increases with depth) and is probably due to an incorrect sound speed estimate.

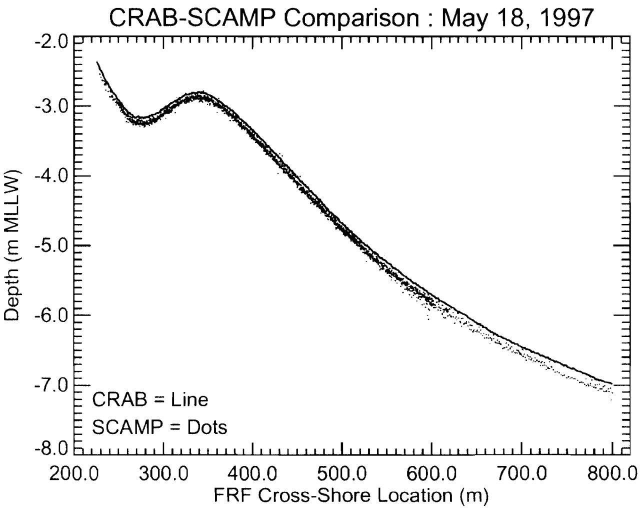

Figure 5. The comparison between SCAMP and FRF CRAB bathymetry along same survey line. The difference is 3.8 cm rms (4.8 cm at 90% probability) and 9 cm mean offset. Approximately 5 cm of that offset has since been attributed to an error in the CRAB height measurement from base of wheel to reference point.

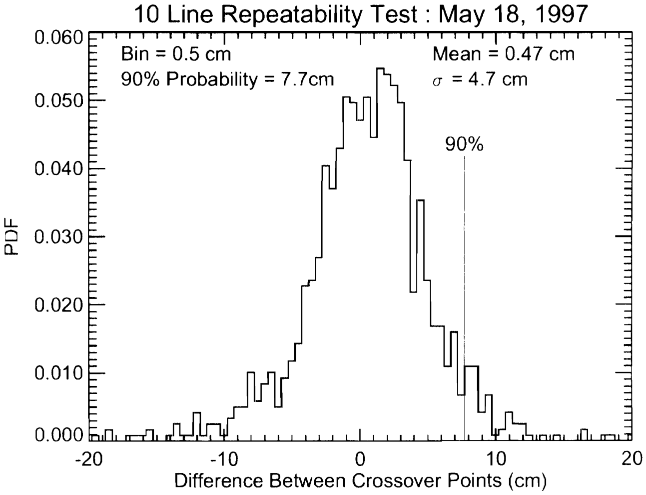

Figure 6. Distribution of the vertical differences obtained from crossover points during the SCAMP 10-line repeatability test of May 18, 1997. The distribution includes 1192 pairs of points that were within 1 m offshore separation. The distribution has a 90% probability of vertical differences less than 7.7 cm, within our goal of 10 cm.

A crossover analysis of the SCAMP bathymetric data from the above test was conducted by identifying depth estimate pairs that were obtained during separate passes and located within 1 m in the offshore direction and 10 m in the alongshore direction. There were 1192 such pairs of points identified. The mean vertical difference between these points was 0.47 cm, the standard deviation of the vertical difference was 4.7 cm, and there was a 90% probability that the vertical difference was less than 7.7 cm. The distribution curve for the vertical difference of the crossover points is shown in Figure 6. The vertical standard deviation of 4.7 cm obtained in this analysis is comparable to that described by GIBEAUT *et al.* (1998). In that study the vertical differences between a newly developed RTK GPS-based bathymetric surveying system and a conventional Zeiss optical bathymetric system had a standard deviation of 6.0 cm and their system produced a 5.7 cm standard deviation for crossover points with horizontal separations of 1 m or less. Our results are similar and within our original design goal of 10 cm vertical accuracy at two-sigma. As a result of these successful tests, in 1998 the FRF contracted Areté to install and test an RTK GPS based bathymetric system aboard their LARC-5. The test was quite successful and subsequently the LARC-5 bathymetric system was converted from the towed sled and optical tracking system to a system similar to that employed on SCAMP.

The vertical component of the time-varying RTK GPS antenna position is a combination of the variations in the still-water level and those induced by boat motions. For frequency scales associated with individual waves, generally 0.1 to 0.3 Hz, the antenna height measurement is the result of a complicated boat response to the surface wave field. The antenna height approximates wave height through boat heave, but also includes unresolved vertical contributions and phase distortion from the pitch, roll and surge of the boat induced by the surface wave field. Still, these are generally small angle rotations (less than 6 degrees) and the RTK GPS antenna aboard SCAMP does provide a reasonable measure of the surface wave spectrum. In Figure 7, a frequency spectrum of the antenna height obtained during the above drift test is compared to an FRF-provided 20-minute average wave spectrum from a nearby Baylor wave gauge. As shown, the two spectra are in close agreement and approximate our measurement goal of 10% accuracy. The curves are quite similar in form with an rms wave height difference (one-sigma) of 3 cm (25 cm rms for the wave gauge and 28 cm rms for SCAMP).

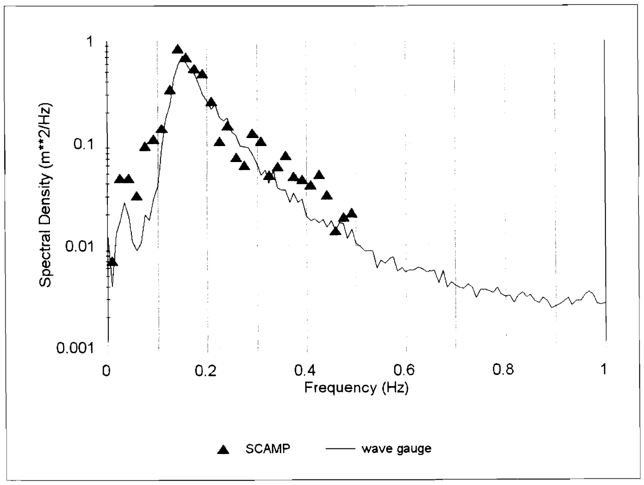

Figure 7. Spectral comparison of surface wave height measurements by (1) SCAMP-mounted GPS antenna and (2) FRF wave staff.

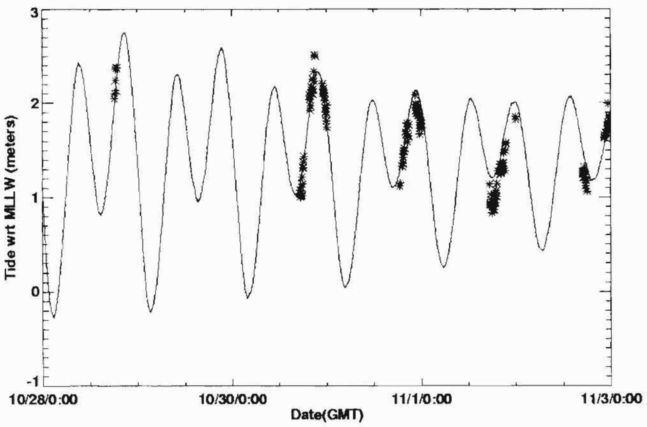

Figure 8. Comparison of low-frequency component of SCAMP-mounted GPS antenna height at Agate Beach, OR with tidal measurements obtained in the nearby Newport, OR harbor. The transfer function thus obtained was used as precise estimator of the water height at Agate Beach for video image registration of the ocean surface.

The slowly varying component of the antenna height measurement is a composite of the still-water level changes due to astronomical tides and locally produced surge and the unrelated boat motion variations caused by boat load conditions and boat course and speed changes. As a general rule, we endeavor to minimize these boat motions. We use the same driver and a uniform speed when conducting surveys. As a result, the low frequency portion of the jetski antenna height measurement follows the tide level very accurately. This became an important attribute during a survey of the nearshore at Agate Beach near Newport, Oregon. For that test, a temporary tide station was deployed to provide mean water level estimates used in the video registration of the surface wave field (*cf.* HOLMAN *et al.*, 1993). The temporary tide station, along with its internally recorded data, were unfortunately lost due to a storm and an alternative approach to estimating the local tide level was implemented using the SCAMP antenna height. The antenna height data for the five separate days that SCAMP was surveying were low pass filtered and compared to the NOS-measured tide in Newport Harbor as shown in Figure 8. The data comparison was used to successfully derive a water level transfer function between our work site at Agate Beach and the harbor. This was not necessary for the bathymetric survey, but rather necessary for estimating the appropriate water level for the ocean surface registration of video measurements that were collected at that site when the SCAMP was not surveying.

An example of a SCAMP-derived bathymetric survey is provided in Figure 9, which is a contour plot of the topography at FRF from the base of the dunes to about 6 m depth. The profiles include ATV beach profiles as well as jetski water depths for 1 km of the coastline near FRF. The result is very smooth, as one would expect from the previous error estimates, and the survey resolves very interesting spatial variations in the nearshore 'front porch' between the shoreline and the trough. A much larger, 10 km bathymetric survey of the nearshore was conducted as part of the 1997 SandyDuck Nearshore Experiment at FRF. The full 10 km bathymetric survey required six days to complete and, during that time (September 28 to October 3, 1997), the RTK GPS percentage of convergent fixes was better than one might have anticipated for operations continuously entering and exiting the high wave region of the surf zone. The Trimble 4400 receiver used on SCAMP includes a status flag output for each reported position to tag whether kinematic convergence has, or has not, been obtained. There are a number of possible causes for loss of kinematic convergence. These include:

1. an excessive GPS antenna tilt due to boat pitch and/or roll,
2. a physical obstruction of the GPS antenna view of the sky (in our case by the driver or the FRF pier),
3. periods of poor PDOP (a measure of the geometry afforded by the observable satellite constellation), and
4. periods of insufficient satellite coverage (5 satellites are required to initialize and 4 to maintain kinematic convergence).

The last two are predictable events. They occur two to three times a day with each event presently producing an operational holiday of about 20 minutes duration. We worked our schedule around these holidays when possible. The combined effect of these operational constraints provided a daily average kinematic convergence rate (number of RTK GPS fixes/total number of fixes) that ranged from 82% to 91%, with a mean of 88% for the full survey. The final survey day was dedicated to filling in the 'missed' survey lines.

Inherent operational errors associated with the EM surface current measurement arise from two ill-defined inputs. The first of these is the hull-induced potential flow past the sensor and the second is the compass deviation curve that is subject to change with each deployment due to extraneous uncom-

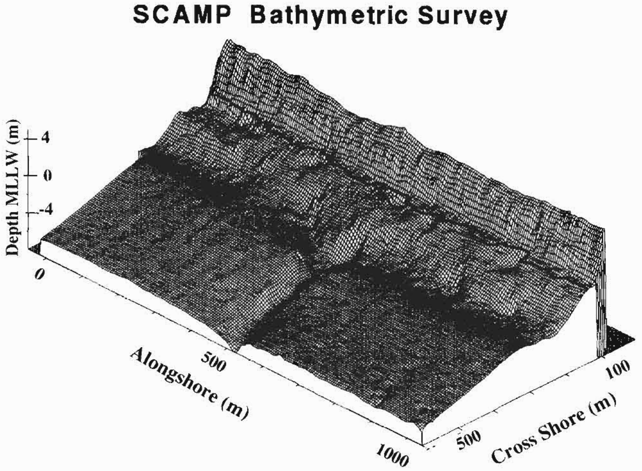

Figure 9. A 3-D contour of the shoreline and nearshore bathymetry at FRF using data acquired from the SCAMP system. The contour is displayed in the FRF coordinate frame. Of note are the nearly continuous nearshore bar and trough and the scouring effect of the 580 m long FRF pier at 500 m alongshore range. The grid points used in the contouring routine provide an average 2 m along-track and 20 m cross-track sampling.

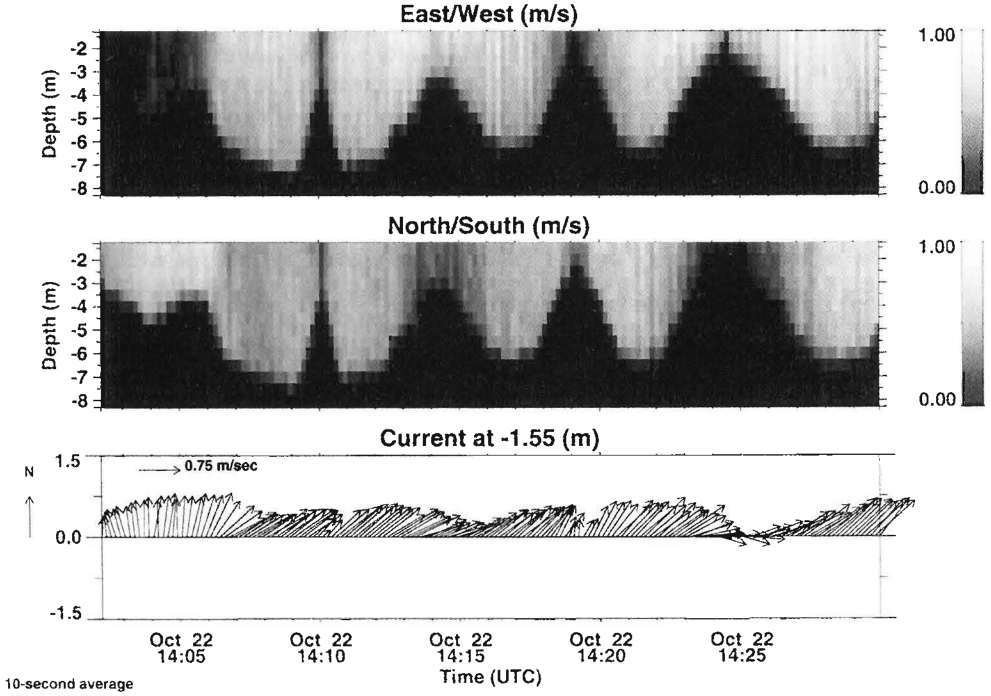

Figure 10. SCAMP-mounted ADCP time series obtained while running multiple transects across shipping channel at Oregon Inlet, NC.

pensated fields on the boat. The quality of the current velocity data was examined by obtaining estimates of the current while running back and forth over a given track and also by comparing the near-surface velocity estimates with a bottom-mounted ADCP. It was found that a residual current always tracked with the boat. The magnitude of this residual was proportional to the speed of the boat, and the obvious source of this bias was the potential flow around the hull. This was about 23% of the boat speed and, once accounted for, the resulting values were markedly improved. We also had a problem with determining the deviation in the compass that was mounted up on the instrument console for use by the driver, and this had to be very carefully compensated as well. Test-specific calibration tests, including reverse course runs in benign current conditions and controlled 360-degree spins on a rotating table (boat and driver), were performed to empirically quantify our ability to estimate these variables. We found that, for current surveys conducted at a nominal 5 knot speed, there was a ± 1.5° direction uncertainty in the compass performance and a ± 5 cm/s uncertainty in the predicted potential-flow estimate. Combined, these operational errors produce a one-sigma current error of ± 8 cm/sec. This is adequate for many inlet and jetty applications, but bias errors of 10 cm/sec can and do occur, so this performance has not met our expectations.

As a result of the above problems associated with the EM surface current measurements, and in an effort to extend our current measurements to full water column profiles, an alternative approach to ocean current measurements has been pursued, one that employs an RD Instruments Workhorse Sentinel ADCP. A time series example of processed current profiles is shown in Figure 10. The data are from multiple transects across the shipping channel on the ocean side at Oregon Inlet, NC, which has a maximum depth of about 8 m. Panel 1 illustrates the east/west component and panel 2 the north/south component. The current vectors measured in the depth bin closest to the surface are shown in the third panel.

A comparison of the velocity profiles from the jetski-mounted ADCP and a bottom-mounted ADCP in the middle of the shipping channel in Oregon Inlet is shown in Figure 11. The water speed during the ebb tide was about 0.75 m/s. The differences between the two data sets are very small, with no apparent bias and less than 5 cm/sec rms in each direction. This is a very good result that meets our accuracy requirement, and the ADCP is normally used instead of the EM current meter.

## CONCLUSIONS

An instrumented jetski, designated the SCAMP, has been developed to provide a rapid and accurate means to obtaining bathymetric and ocean current surveys. The system has successfully demonstrated the capability to extend RTK GPS survey accuracy into the nearshore, including the surf zone. By using RTK GPS referencing to the WGS84 ellipsoid, the SCAMP system offers a substantial improvement in spatial resolution over standard survey launch, single-beam profiling systems by eliminating the requirement to apply spatial averaging and tidal reference to compensate for boat motion and water level variations. The versatility of SCAMP has

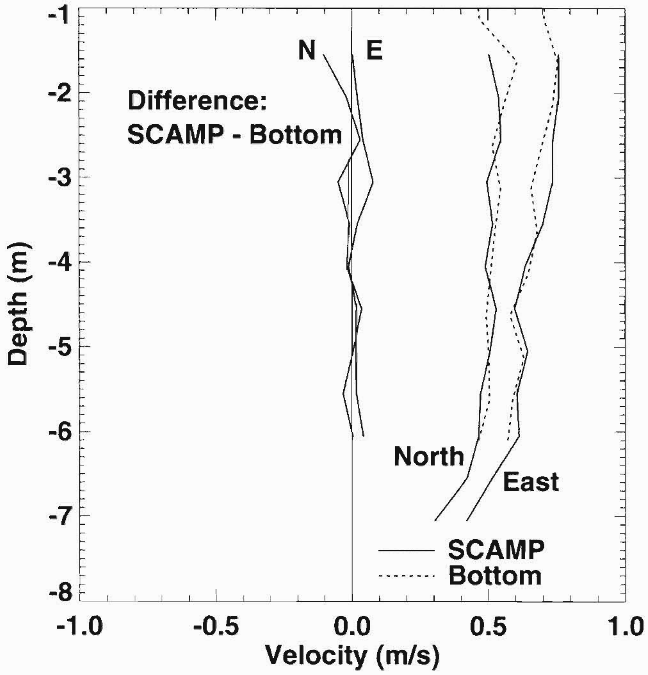

Figure 11. An ADCP water column profile comparison between the SCAMP-mounted ADCP and a nearby bottom-mounted ADCP in the shipping channel at Oregon Inlet NC.

been further illustrated by the installation of an ADCP to provide a vertical profile of horizontal currents in the water column.

Comparison tests with standard independent measurement systems were undertaken to quantify the performance of SCAMP bathymetry and current measurements. The bathymetric measurements have been compared to survey lines occupied concurrently by the FRF CRAB. After an error adjustment in the CRAB height measurement, the differences were 4 cm in the mean and 5 cm at 90% probability. A crossover analysis for SCAMP bathymetric measurements separated by less than 1 m offshore (10 m alongshore), produced a 90% probability of vertical differences less than 7.7 cm. Use of an EM surface current sensor deployed off the stern quarter of SCAMP produced measurement errors of the order of 10 cm/s, and this did not meet our performance expectations. This was attributed to difficulties in adequately defining the hull potential flow and the heading sensor deviation curve. However, the use of an ADCP for obtaining velocity profiles has exceeded the performance requirements, as demonstrated in a comparative test with a bottom mounted ADCP of similar design. The computed differences from that test had negligible bias and about 5 cm/s rms difference.

The key to the SCAMP system performance is the precise navigation and positioning derived from RTK GPS, a component of the system that has proven to be very reliable. While conducting surveys in the difficult surf environment, the RTK GPS system has consistently provided kinematic fixes of position at a nearly 90% rate. This has allowed the SCAMP survey system to provide an average survey coverage rate in excess of 2 km$^2$/day.

## ACKNOWLEDGEMENTS

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